VEGETATION AND LAND-USE CHANGE IN NORTHERN EUROPE DURING LATE ANTIQUITY: A REGIONAL-SCALE POLLEN-BASED RECONSTRUCTION

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Abstract

This chapter presents an overview of land cover and land use change in northern Europe, particularly during Late Antiquity (*ca*. 2nd-8th c. A.D.) based on fossil pollen preserved in sediments. We have transformed fossil pollen datasets from 462 sites into eight major land-cover classes using the pseudobiomization method (PBM). Through using pollen-vegetation evidence, we show that north-central Europe, lying outside the Roman frontier (the so-called 'Barbaricum' region), remained predominantly forested until Medieval times, with the main clearance phase only starting from *ca*. A.D. 750. This stands in contrast to north-west Europe, both inside (France/England) and outside (Scotland/Ireland) the Roman imperial frontier; here a majority of forested land was already cleared prior to antiquity. The implications of this are that Roman expansion into the periphery of the empire largely took over existing intensive agrarian regions in the case of 'Gaul' (France) and 'Britannia' (England and Wales). Pre-existing land-use systems and levels of landscape openness may have played a role in directing the expansion of the Roman empire northwards into Gaul and Britannia, rather than eastwards into Germania. After the period of Roman occupation, partial reforestation is evident in some areas.

INTRODUCTION

Regional landscape characteristics may have been important in influencing human land use patterns and the advancement of the Roman frontier across Europe. The aim of this study is to explore land use change on a regional scale, within and beyond the Roman frontier, in north-west and north-central Europe. For this, we use multiple pollen records in order to compare the timing of shifts in land use patterns in relation to historical and archaeological evidence of changing human activity during Late Antiquity (*ca*. 2nd to 8th c. A.D.), within the longer-term context of the Mid-Late Holocene (4000 B.C. until present). Previous pollen-based syntheses of land-cover change for central and northern Europe have highlighted the importance of human land use in influencing patterns of Mid-Late Holocene vegetation change.[1]

The European continent has undergone significant landscape alterations throughout the Holocene as a result of climatic fluctuations and human land-use changes. Fossil pollen, preserved in lake and peat sediments, has provided a valuable tool in understanding past vegetation change, and various approaches have been developed to turn pollen data into records of quantified vegetation cover and land use change.[2] These methods can allow us to consider the time at which human land use began to alter vegetation at both local and regional scales.

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[1] E.g. Behre (**1988) [1988 in biblio**]; Berglund *et al.* (1996); Berglund (2003).

[2] Quantified vegetation cover: e.g. Marquer *et al.* (2014); Trondman *et al.* (2015). Land-use change: e.g. Fyfe *et al.* (2015).

Synthesis of pollen records from northern Europe has the potential to explore human land use and vegetation change. For example, initial forest loss at the regional and continental scale is recorded from *ca*. 4000 B.C., as a result of Neolithic land use activities, such as tree clearance for agriculture.[3] Comparison with radiocarbon-based demographic data at the national scale, has confirmed the relationship between population and land cover change from prehistoric Britain, and a relationship between secondary woodland regeneration and population in southern Germany.[4] Approaches that quantify vegetation using pollen data, have indicated that there was an increase in open land between 4000 and 1000 B.C. in temperate Europe.[5] Furthermore, an important intensification of land use, reflected in greater forest clearance and the establishment of pastoral and arable land use, has been identified beginning in the Late Iron Age (*ca*. 250 B.C.).[6] Thus, by the start of the late antique period, the landscape of temperate Europe was already notably transformed. Continent-scale reconstruction indicates that forest cover was relatively stable during Late Antiquity. Following the 'Migration Period' (from around A.D. 400), there was a downward trend in forest cover, as arable and pasture / grassland increased in extent from *ca*. A.D. 750,[7] and it was during Medieval times that Europe's pre-industrial landscape was established. These changes primarily reflect patterns of human land use change, both in mode of production and intensity of land use.

The Romans conquered the non-Mediterranean area of 'Gaul' under Julius Caesar during the 1st c. B.C. From there he went on to lead the first invasion of Britain around 55 B.C.,[8] but Britain was not incorporated into the empire until *ca.* A.D. 43, with the full extent of the western Roman empire established by *ca*. A.D. 100. Randsborg has described the development of the villa system of large agricultural estates under the empire, which required abundant resources and workers.[9] In the Roman period in north-west Europe, settlements were mainly concentrated on good grain-growing soils with intensive cultivation of cereals, along with long-distance trading.[10] The centuries of the Roman empire's rise coincided with general climatic favourability (the Roman optimum: 100 B.C. to A.D. 200) and warm mean summer temperatures.[11] There has been much debate over the relative importance of climate changes and human land use pressure on the vegetation of Europe; for example, Huntley argued that climate was more important until around A.D. 1000,[12] although this is hard to reconcile against the abundant evidence for intensive human land use of the continent from archaeological and historical sources. Equally, Berglund demonstrated that human impact events across north-west Europe were not concordant with periods of Holocene climate changes.[13]

In north-central Europe Germanic resistance and military conflicts—such as the battle of Teutoburg Forest in A.D. 9, in which three Roman legions were ambushed and destroyed—restricted Roman expansion to the natural frontier of the river Rhine. Similarly, the Romans made no concerted attempt to occupy Ireland, and although Scotland was invaded, the northern defensive frontier of the empire was eventually established at Hadrian's Wall, in close proximity to the present-day border between England and Scotland. The western Roman empire eventually declined during the 5th c. A.D., with far reaching social impacts, and led to the collapse of trade networks, the decline of cities, and the

[3] Behre (1988); Woodbridge *et al.* (2014a); Fyfe *et al.* (2015); Gaillard *et al.* (2015).
[4] Prehistoric Britain: Woodbridge *et al.* (2014a). Southern Germany: Lechterbeck *et al.* (2014).
[5] Marquer *et al.* (2014) and Trondman *et al.* (2015).
[6] Fyfe *et al.* (2015).
[7] Fyfe *et al.* (2015).
[8] Russel (2005).
[9] Randsborg (1991).
[10] Randsborg (1991).
[11] Roman optimum: McCormick *et al.* (2012). Warm summer temperatures: Luterbacher *et al*. (2016).
[12] Huntley (1990).
[13] Berglund (2003).

advent of the so-called post-Classical 'Dark Ages' across Europe. The amalgamation of pollen datasets across broad sub-continental areas, and sub-regions within Northern Europe, allows differences in the timing of vegetation shifts to be identified in relation to these historical-cultural changes.

METHODS

Pollen Analysis and Pseudobiomization (PBM)

Fossil pollen preserved in peat and lake sediments provides a proxy for vegetation and landscape change through time. Numerous radiocarbon-dated pollen records from the European Pollen Database (EPD)[14] have been synthesised and transformed for a selection of regions (fig. 1) to reflect patterns in different regions encompassing areas that would have been within and outside the margins of the Roman empire. The Pseudobiomization Method (PBM) has been used in order to identify regional-scale vegetation changes. This includes 190 sites in north-west Europe and 225 from north-central Europe, which are split into a number of sub-regions. 'Germania' covers the region of north-central Europe from the Rhine in the west to Vistula (present day Poland) in the east, the Danube in the south to the Baltic Sea in the north. 'Gaul' covers France, Belgium, small parts of south-west Germany and the southern Netherlands. Although this is an extensive dataset, there is spatial bias in the distribution of sites, with limited coverage of EPD sites in some regions, such as lowland England. The PBM provides a relatively simple and easily applied approach for turning complex pollen data into Land-Cover Classes (LCCs) related to human land-use change at 200-year time intervals.[15] The key strengths of the PBM are that it can be easily applied to large datasets, is informative about broad-scale vegetation change through time, and has been developed to indicate anthropogenically-induced land-cover change by incorporating taxa that are indicators of land uses, such as agriculture and grazing. The approach is less complex than some other methods for the transformation of pollen to vegetation cover data, which rely on a detailed understanding of the differences in pollen productivity and dispersal between plant taxa. This is the case with the REVEALS (Regional Estimates of VEgetation Abundance from Large Sites) approach,[16] which incorporates differences in pollen production based on PPEs (Pollen Productivity Estimates), albeit for a more restricted number of taxa.

The correlation and correct interpretation of pollen records is dependent on good chronological control from radiocarbon-dated core sequences. Chronologies constructed in recent years have been used to sum the pollen count data from each site into 200 year time windows for the records analysed in this study.[17] The PBM approach is based on assigning each pollen taxon to one of a series of LCCs (table 1)—such as *Quercus* to deciduous woodland, or *Secale cereale* to arable land-cover)—and identifying which LCC has the majority of pollen grains assigned to it. This becomes the 'dominant' land-cover type for that particular pollen sample level within a core sequence, which can include one of eight classes (table 2). Additionally, broad-leaf forest was down-weighted (x 0.6) and arable / disturbed land was up-weighted (x 1.3) in the dataset. This partly compensates for the over- and under-production of pollen in these broad groups, and is based on the results of a comparison of modern pollen and remotely-sensed vegetation.[18] Semi-open and mixed vegetation LCCs are defined using a threshold value between the sum of closed and open land-cover,[19] which is a proxy for relative change in

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[14] Leydet (2007-16).
[15] For more detail of this see Fyfe *et al.* (2010) and Woodbridge *et al.* (2014a).
[16] Sugita (2007); Gaillard *et al.* (2010).
[17] Giesecke *et al.* **(2014)** and Leydet (2007-16).
[18] Woodbridge *et al.* (2014b).
[19] Woodbridge *et al.* (2014b).

vegetation openness ranging between -100 and +100. This has been presented stratigraphically as symbols, indicating the assigned LCC for a selection of sites representing each case study region. The proportion of each LCC represented in each 200 year time window has been calculated to reconstruct spatially aggregated records of land-cover change for different regions of north-west and north-central Europe (fig. 1). The results are presented as the percentage of samples assigned to each LCC through time, both for multiple records within each region, in order to create a regional average, and also for individual pollen records, in order to show more local trends.

Historic Geographic Forest Maps / Domesday Records

Historic records of forest cover have been compared against the pollen-inferred land-cover change reconstructions, to test their ability to accurately reconstruct vegetation. The percentage of forest, for A.D. 700-900 and A.D. 1900, covering central-northern Europe (highlighted by the grey box in fig. 1) was calculated from a digitised historic geographic forest map.[20] Values for woodland percentage were also obtained from Rackham, who provides details of land cover in A.D. 1086 and 1895, and is partly based on the historic Domesday record of English counties.[21] The use of these historic sources is limited by the data collection approaches used (e.g. place name evidence), and consequently the area mapped as forest may not represent true forest cover, particularly for the early Medieval period.

RESULTS

Relative change in the abundance of different land-cover types throughout Late Antiquity is illustrated in figures 2 and 3, which is placed within the context of the Mid-Late Holocene. Regional variation in the timing and amplitude of forest loss and increasing open land from around 4000 B.C. is demonstrated in figure 2, which summarises the percentage of pollen samples assigned to closed, semi-open, and open vegetation LCCs throughout the Mid-Late Holocene. The percentage of sites assigned to forest classes in north-west Europe was as low as 20% by *ca*. 450 B.C. However, sites in north-central Europe remained forested for longer, with high forest values (above 40%) persisting until around A.D. 950.

Separate analyses for sites in England and Wales, and Scotland and Ireland, indicate that these regions became more open earlier in the records in comparison with sites from France and Belgium. Separate analyses for parts of the central European region show a similar trend to the pattern shown for the amalgamated central European dataset, although the records from southern Sweden and Denmark show an initial decline in forest cover earlier (around A.D. 300) than the other sub-regions. Individual open LCCs are shown in figure 3, which illustrates how different open vegetation land-cover types dominated in different areas throughout Late Antiquity. For example, pasture / natural grassland was the principal LCC in England and Wales, with values reaching almost 80% by *ca*. A.D. 1350, whereas heath / scrubland was more abundant in records from Scotland and Ireland. Arable land was relatively more significant in continental Europe, especially inside the Roman frontier (i.e. in 'Gaul') (fig. 3).

Over the Mid-Late Holocene timescale (fig. 2) the different regions analysed vary in the timing of changes in the main land-cover types. When analysed separately, records indicate that England was significantly more open earlier in the record in comparison with other regions, whereas the dominant vegetation type in Scotland and Ireland is semi-open land-cover. When the central European dataset is split into smaller sub-regions, all areas show similar patterns, with longer persistence of forest classes until around A.D. 500, although the semi-open class increases earlier in the records from southern Sweden. A greater percentage of samples have been assigned to mixed open vegetation for the

[20] Schlüter (1952); Darby and Terrett (1954); Thomas (1970).
[21] Rackham (2003).

combined records from north-west and north-central Europe, but values never reach above 20% for any region for this mixed LCC. Therefore, pollen samples dominated by open vegetation indicators appear to typically fall into distinct classes, such as heathland or pasture / grassland in these regions.

Figure 4 shows a representative selection of individual pollen records from different regions of northern Europe, in order to highlight variations in vegetation history across the wider landscape. The pollen sites show relative change in landscape openness and the assigned LCC for each sample, and indicate similar trends to those recognised at the amalgamated regional level (site location numbers are provided on figure 1). The graphs provide an indication of vegetation openness, but do not reflect fully quantified vegetation. The LCC symbols plotted to the right in each graph, with a score between 0 and 100, indicate more closed landscapes; symbols plotted within the ± 20 range of 0 represent semi-open vegetation, and symbols plotted to the left of each plot (-100 to 0) represent open vegetation types.

Figure 4 shows how north-west Europe was an open landscape earlier in the Holocene, whereas many areas of north-central Europe (particularly Germany, Poland and the Czech Republic) remained forested for longer, but there is variation in the types of open / closed LCCs assigned, and the timing of changes varies between sites. Some records from Germany (Steerenmoos and Grosser Treppelsee) were dominated by mixed forest, whereas other records from the same region were assigned to broad-leaf forest (e.g. Lüttersee). Holzmaar, located inside the Roman frontier, was dominated by semi-open vegetation prior to antiquity according to the PBM results. Within these records, the main shift from closed to semi-open LCCs in Germany and Poland seems to have occurred around A.D. 1000, whereas semi-open LCCs define the record from Denmark (Lake Solsø) from 2500 B.C.

Differences in the timing of shifts and the types of forest LCCs are also shown in the two records from Sweden in figure 4: Ageröds Mosse is defined as deciduous forest, whereas Holtjärnen is mixed forest, and both remain semi-open, with no open LCCs assigned later in their records. Similarly, the records from north-west Europe show variation in the dominant LCCs and the timing of changes in their records. For example, Dallican Water from Scotland is assigned to heath / scrubland from 4000 B.C., whereas these open LCCs do not appear until later in the other records from Scotland and Ireland (*ca*. A.D. 600). However, as Dallican Water is located on an island off the north coast of Scotland, the different environmental characteristics and degree of exposure to prevailing winds may have influenced this record, which has been recognised as relating to decreased tree abundance in pollen records from Scottish islands.[22] The forest LCC types assigned to sites in north-west Europe (shown in figure 4) are all broad-leaf, however, the open LCCs vary regionally. Sites in England and Wales are defined by pasture / natural grassland, whereas sites in France and Switzerland include more semi-open land, arable / disturbed land and mixed open vegetation.

The woodland percentages obtained from Rackham (fig. 5) indicate that tree cover in England decreased somewhat between A.D. 1086 and 1895.[23] However, the pollen-inferred PBM closed sum, which provides an indication of forest cover, shows higher values than those provided by Rackham (fig. 5a). Differences in the exact time periods covered by these datasets, and the limitations of inferring past forest cover from historic sources, may account for the differences in these values. The comparison between an historic forest map for north-central Europe (mainly covering Germany) (fig. 1) and the PBM closed sum (fig. 5b) indicates similar values around A.D. 700-900 and A.D. 1850-1900, showing a decrease in forest cover between these dates, but also shows that values remained high (above 30%) in the more recent time period. The forest map for A.D. 1850-1900 is likely to be a more reliable historic source, whereas the map for A.D. 700-900 may show significant over/under estimates of forest cover. However, when considering relative changes, both the pollen data and the historic maps show a decline in forest cover between these dates.

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[22] Lowe and Walker (1986).

[23] Rackham (2003).

DISCUSSION

Regional and Local Vegetation Changes Inside and Outside the Western Roman Empire

The sub-continental and regional-scale changes evident in the PBM-transformed pollen records for north-central and north-west Europe, highlight the extent of spatial and temporal variability that existed in land use and forest loss patterns throughout the Mid-Late Holocene. The greater percentage of samples assigned to forest LCCs in north-central Europe (Germany, Poland, Czech Republic, southern Sweden and Denmark), indicates that a more densely forested landscape persisted for longer in all areas (excluding parts of southern Sweden and Denmark) in comparison with north-west Europe (England, Wales, Scotland, Ireland, France and Belgium), where open vegetation types are abundant much earlier in the records. Thus, prior to antiquity, it appears that there was already greater intensity of human land use for agriculture in these north-western areas.

These patterns are similarly reflected in other broad-scale vegetation reconstructions for northern Europe.[24] The patterns of landscape change identified in the PBM results (figs. 2, 3 and 4) are also reflected in numerous individual pollen sequences from temperate Europe. For example, in a record from northern England (Gormire Lake), a pattern indicating forest loss was identified from 200 B.C. that was contemporaneous with increased grass pollen and various other agricultural indicators, which was followed by forest recovery from *ca*. A.D. 500.[25] Similarly, another record from northern England showed three Late Neolithic–Bronze Age woodland clearance phases from *ca*. 2290 B.C., with Late Iron Age clearance and agricultural intensification from *ca*. 300 B.C., and a peak period of clearance *ca*. 90 B.C. until A.D. 50.[26] This highlights that forest removal was extensive in England prior to Late Antiquity, and the patterns described are consistent with the amalgamated PBM results for England.[27]

In a study of long-term human impacts on landscape and vegetal biodiversity in the Auvergne region of France, using pollen data, a decline in forest cover from around the 2nd c. A.D. was identified, along with a progressive period of widespread woodland exploitation for agro-pastoral purposes.[28] Woodland clearance was identified as already evident prior to this period, with pastoral and arable agriculture apparent at the local and regional scales. These kinds of patterns reflect the overall regional trends identified in the PBM results for north-west Europe. Individual pollen records from north-central Europe indicate similar patterns of land use change to those in the records from north-west Europe, but with differing impacts on forest cover. For example, in a pollen record from the Eifel region of Germany close to the Roman frontier (Holzmaar) (fig. 4: site 9), a high percentage of trees and shrubs was identified, but with variations in the main tree types throughout Late Antiquity.[29] However, this record also shows persistent grasses and agricultural pollen types throughout this period, followed by forest recovery from *ca*. A.D. 200. The PBM-assigned LCCs for this record (fig. 4) indicate that the forest type remained broad-leaved, with a shift to semi-open vegetation through Late Antiquity, and a subsequent return to forest LCCs around A.D. 500.

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[24] E.g. Trondman *et al.* (2015); Fyfe *et al.* (2015).
[25] Oldfield *et al.* (2003).
[26] Yeloff *et al.* (2007).
[27] See Rippon and Fyfe (this volume) for a discussion of pollen records from the British Isles covering Late Antiquity.
[28] Miras *et al.* (2015).
[29] Litt *et al.* (2009).

In a pollen record from Poland, continuous human land use was identified between the 7th c. B.C. and the 10th c. A.D., linked to agriculture.[30] Therefore, human land use appears to have been significant throughout Late Antiquity in some parts of north-central Europe (Germany and Poland in particular) and the records mentioned above provide evidence for considerable agriculture in north-central Europe throughout this time period. This demonstrates the added value of a synthetic approach, using multiple pollen records covering large areas, and the sub-regions within these areas, which allows interpretations between regions.

The inter-regional comparisons provided by the PBM analyses can help us to explore where and when some areas experienced greater forest loss than others. Unlike the individual pollen records discussed above, the amalgamated PBM-based vegetation reconstruction shows that while there is evidence of continuous agriculture in north-central Europe, its impact on forest cover was not as significant as in parts of north-west Europe. Using the REVEALS approach, it was found that the degree of anthropogenic transformation of forests to cultivated and grazing land in northern Europe was significantly higher than inferences based on pollen percentages alone.[31] However, the REVEALS results still show high values of forest cover for the A.D. 1250-1600 (350-700 CAL. BP) time period in northern Germany, with values above 40% for summer-green trees.[32]

The division of the PBM pollen dataset into regions inside and outside the Roman frontier indicates that the vegetation of Scotland and Ireland remained partly open for longer, and that open land was the most important land-cover type in England and Wales throughout Late Antiquity. Both regions had significantly more open land in comparison with north-central Europe at this time (fig. 2). The main difference between these two regions was the type of open land-cover: namely, heath / scrubland in Scotland and Ireland, whereas pasture / grassland was the main LCC in the available EPD records from England and Wales. Heath / scrubland is evidently of lower economic value in comparison with pastureland.

In an analysis of 73 pollen records from the British Isles using the REVEALS approach, it has been shown that Britain had a greater degree of landscape openness at the regional scale than areas across mainland Europe.[33] This study also highlighted the considerable spatial bias in the dataset towards wetland areas (such as fens) and uplands in the British Isles, and this may partly explain the higher estimates of landscape openness for the region. The patterns in the PBM results for different sub-regions of northern Europe may be explained by differences in certain landscape characteristics. For example, flat expanses on clay-rich soils have been described as areas with the most intensive agricultural impact, with hilly areas remaining rich in forest, and poor sandy soils becoming dominated by heathland, for example, in Denmark and southern Sweden.[34] Semi-open vegetation is the most abundant class in the PBM results for southern Sweden and Denmark (fig. 2), and the patterns identified in the PBM results for southern Sweden are different to other parts of the central European study area. The quantified land-cover reconstruction based on the REVEALS approach suggests that by the Late Bronze Age / Early Iron Age, significant areas of southern Sweden were under human use for crop cultivation and pastures,[35] which includes areas that the PBM approach has defined as semi-open vegetation. In some western parts of Europe the most pronounced human impacts on vegetation took place during the Roman period; however, in Ireland renewed agricultural activity occurred later, after

[30] Szal *et al.* (2014).
[31] Trondman *et al.* (2015).
[32] Trondman *et al.,* 2015).
[33] Fyfe *et al.* (2013).
[34] Berglund *et al.* (2003); Gaillard *et al.* (2015).
[35] Gaillard *et al.* (2015).

around A.D. 300.[36] In continental Europe, regional forest regeneration has been identified during the 'Migration Period' (A.D. 400-550) in marginal areas of Denmark, southern Sweden, the Baltic Sea coast, north-east Germany, and northern Poland.[37]

When multiple fossil pollen sequences are analysed over broad regions, the results support the hypothesis that landscapes differed within and outside the Roman frontier, with greater open land inside the frontier prior to Roman advancement into this region, and continued persistence of forested land for longer outside of the frontier in continental Europe, particularly in what is now Germany, Poland and the Czech Republic. Figure 4, which is based on a selection of individual pollen sequences, highlights that within each region there are differences between individual sites. Three out of the six selected sites in Germany show evidence of forest loss prior to antiquity (around the 8th c. B.C.), while three others show this only occurring in the Medieval period (from around the 5th c. A.D.). However, in comparison with England, none of the six German sites show predominantly open landscapes through Antiquity; even those that had experienced some clearance were still partly forested.

Temporal and spatial changes in forest cover will have also been influenced by climatic variability, but this is likely to have been more significant over longer multi-millennial timescales than during the 1st millennium A.D. Associations have been made between climatic conditions and the advance and retreat of the Roman empire,[38] . Paleoclimate records also reveal regional variability in climate trends through Late Antiquity across Europe.[39]

Vegetation Change and the Expansion / Retreat of the Cultural Landscape

The last 2500 years (from around 550 B.C.) is described as a period characterised by the widespread transformation of Europe's land cover associated with human land use.[40] This is reflected in shifts in pollen records from closed forest to open land-cover,[41] and also coincides with increased human population levels.[42] Considerable forest loss had therefore already occurred in north-west Europe before the arrival of the Romans, as a result of land-use and land-cover change during later prehistory, which accelerated during antiquity.[43] There are numerous driving forces that would have influenced the pattern of Roman expansion and the regions conquered and incorporated into the empire. For example, as demonstrated in the pollen record, lowland Britain was already a largely cleared agricultural landscape in 55 B.C. 'Britannia' may therefore have appeared economically valuable, whereas much of 'Germania' was still densely forested at this time.

The causality behind expansions or regressions of the cultural landscape, and land-use changes, is complex.[44] However, one possibility is that Britain was invaded and occupied by the Romans due to the economic gains that were offered by an already cleared agricultural landscape, with many existing rural settlements that could be incorporated into the Roman villa system. **There was a large degree of regional variation in Romano-British agriculture, with significant diversity of Roman rural settlement across the landscape**.[45] The Roman army also experienced setbacks in Germania, such as the Battle of the Teutoburg Forest in A.D. 9, one of the Roman army's greatest military defeats, and

[36] Behre (1988).
[37] Gaillard *et al.* (2015).
[38] E.g. McCormick *et al.* (2012).
[39] E.g Luterbacher *et al.* (2016); Labuhn *et al.* (this volume).
[40] E.g. Fyfe *et al.* (2015).
[41] E.g. Marquer *et al.* (2014).
[42] E.g. Collard *et al.* (2010).
[43] E.g. Woodbridge *et al.* (2014a).
[44] Berglund (2003).
[45] Smith *et al.* (2016).

which discouraged further expansion into this region. The dense forests that still existed east of the Rhine were likely to have been an impediment to the Roman armies and an asset to Germanic tribes; the latter may have had a military advantage thanks to a lack of battles in open terrain. The pollen evidence therefore implies that differences in regional landscapes, and particularly in the economic value of agricultural and forested land, may have influenced the spatial pattern of Roman expansion.

At the northern European scale, it has been shown that there was a reduction in the pace of forest clearance between *ca*. 50 B.C. and *ca*. A.D. 600,'.[48] This was followed by renewed forest clearance during the Medieval period, particularly in central Europe, which had remained largely forested throughout Late Antiquity. The PBM results show evidence of reversals in the total forest cover for north-central and north-west Europe, but the changes in the total forest cover were small during and after Late Antiquity, according to the records analysed at an amalgamated regional scale, even if individual sites show periods of reforestation.[49] When the Rhine frontier collapsed in A.D. 406 the Romans began to withdraw from Britain and never returned.[50] The post-Roman decline of agriculture and the gradual appearance of new land-cover types leading to reforestation, would have been spatially and temporally variable. During the period covering the fall of the Roman empire, woodland levels stabilised in the pollen records for north-west and north-central Europe, until a further more dramatic decline in forest cover over the last 1100 years (since *ca*. A.D. 950). A comparison with historic records using the forest map for central Europe and Rackham's land cover records for Domesday England, implies that there was still a tangible difference in forest cover between England and Germany in Medieval times.[51]

CONCLUSION

The contrasting vegetation reconstructions for north-west and north-central Europe indicate significant regional variation in the timing and extent of forest loss between these regions. Many forests in England and Wales ('Britannia') and France ('Gaul') were converted to arable or pasture land by existing Celtic populations in the Iron / Bronze Ages. By the 1st c. B.C., both of these regions had dense rural populations and productive agrarian economies that would have made them appealing targets for Roman imperial expansion. These areas also may have been easier to conquer and to control militarily by Roman invaders than the still-densely forested lands east of the Rhine.

The PBM-inferred land-cover reconstruction indicates that much of north-central Europe remained densely forested until *ca*. A.D. 950, whereas north-west Europe, particularly Britain, was already an open landscape prior to the Roman arrival. During the centuries after the end of Roman imperial rule, the decline in forest cover was halted or reversed in many but not all regions; in most of northern Europe there is evidence of forest recovery in the period before the main onset of Medieval economic and demographic growth. Forests, or the lack of them, may therefore have been both a cause and a consequence of the nature of Roman imperial expansion, and its post-antique retreat and the societal reorganisation that followed.

ACKNOWLEDGEMENTS

[48] Fyfe *et al.* (2015).
[49] E.g. Oldfield *et al.* (2003).
[50] Nicholas (2014).
[51] Schlüter (1952); Thomas (1970); Rackham (2003).

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FIGURES AND TABLES

Figures

Fig. 1. Northern Europe case study areas with fossil pollen site locations (numbers reflect sites presented in fig. 4). Symbols indicate sites grouped for analyses. The shaded area represents the Roman imperial frontier and the grey box highlights the area of the historic forest map: Schlüter (1952); Thomas (1970).

Fig. 2. Total forest, semi-open and open vegetation percentage for sites grouped for north-west Europe: England + Wales, Scotland + Ireland and France + Belgium, and north-central Europe: Germany + west Czech Republic, Poland + east Czech Republic and southern Sweden + Denmark. Values based on the percentage of samples assigned to each land-cover class (LCC) using the pseudobiomization (PBM) approach: 7000 cal. CAL. BP (5050 B.C.) to modern. The grey box highlights the time period covered by Late Antiquity.

Fig. 3. Percentage of samples assigned to each land-cover class (LCC) using the pseudobiomization (PBM) approach for LCC5 (heath / scrubland), LCC6 (pasture/natural grassland), LCC7 (arable / disturbed land) and LCC8 (mixed open vegetation) based on sites grouped for north-west Europe: England + Wales, Scotland +

Ireland and France + Belgium, and north-central Europe: Germany + west Czech Republic, Poland + east Czech Republic and southern Sweden + Denmark: 7000 cal. CAL. BP (5050 B.C.) to modern. The grey box highlights the time period covered by Late Antiquity.

Fig. 4. PBM score: closed forest sum minus open vegetation sum (proxy for vegetation openness) for pollen samples summed into 200 year time windows for a selection of sites from a) north-central Europe (all sites are located outside of the Roman frontier, and some are positioned close to the border (Holzmaar and Steerenmoos); and b) north-west Europe, which includes sites both within (France, England and Wales) and outside (Scotland and Ireland) the Roman frontier. The symbols represent the assigned Land Cover Class (LCC). Symbols plotted to the left indicate open land-cover types, and to the right indicate closed land-cover types. The grey boxes highlight the period 7000 cal. CAL. BP (5050 B.C.) to 600 cal. CAL. BP (A.D. 1350).

Fig. 5. a) Woodland percentage by English county, according to Rackham (2003), with pollen-inferred closed sum based on the pseudobiomization (PBM) approach and historic woodland percentage for Devon and averaged for England, from Rackham (2003); b) comparison of a historic forest map (Schlüter (1952); Thomas (1970)) for north central Europe, and the pollen-inferred PBM forest sum for the same region.

Tables

Table 1. Land Cover Classes (LCCs) defined for the pseudobiomization (PBM) method with assigned pollen taxa.

Table 2. Land Cover Classes (LCCs) defined for the pseudobiomization (PBM) method.

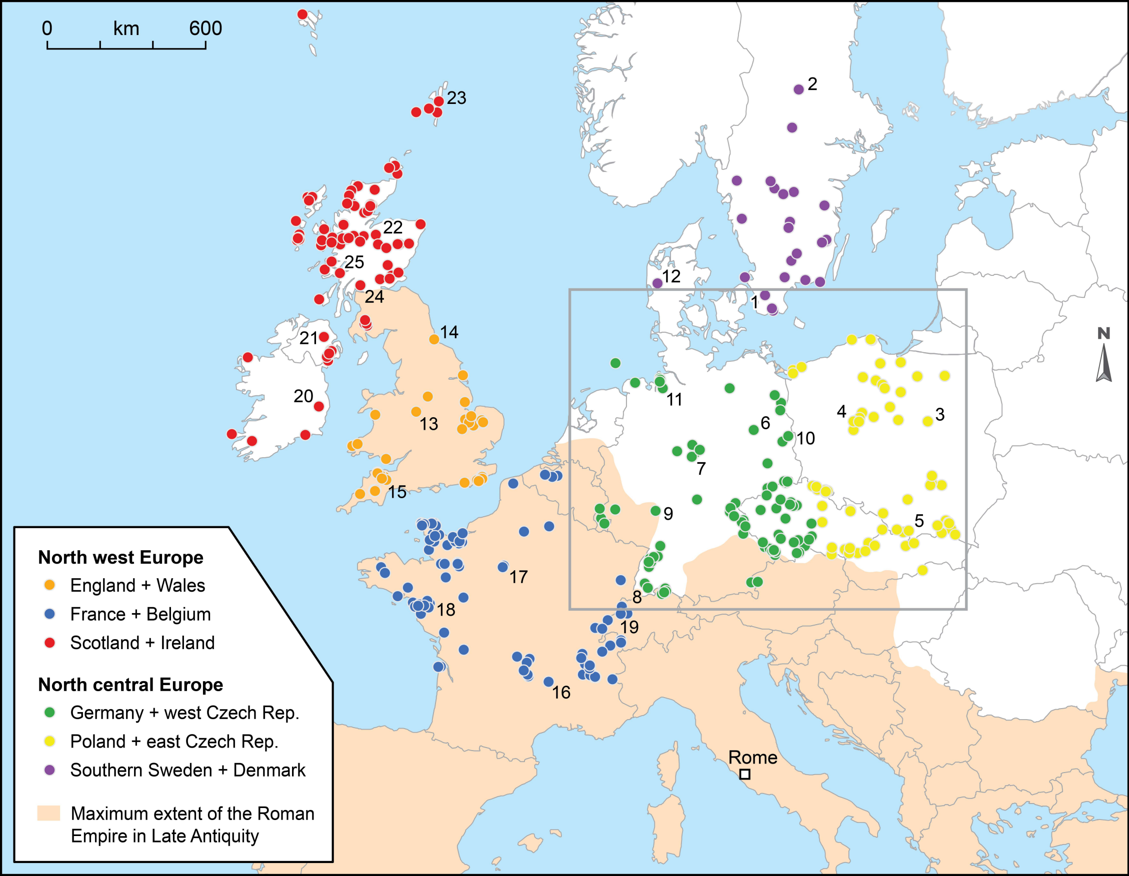
Table 1 Land cover classes (LCCs) defined for the pseudobiomization (PBM) method with assigned pollen taxa

	Land Cover Class	Pollen taxa assigned for PBM
Closed LCCs		
LCC1	Needle-leaf forest	*Abies, Cupressaceae, Larix, Picea, Pinaceae, Taxus*
LCC2	Broad-leaf forest	*Acer, Aesculus, Alnus, Amygdalus, Anacardiaceae, Arceuthobium, Betula, Buxus, Carpinus, Castanea, Celtis, Cercis siliquastrum, Corylus, Crataegus, Daphne,* deciduous *Quercus* , *Euonymus, Fagus, Frangula, Fraxinus, Hedera, Ilex, Juglans, Liquidambar, Liriodendron, Lonicera, Malus, Morus, Myrica,* Myrtaceae, *Nyssa, Olea, Parrotia, Platanus, Populus, Prunus, Pulmonaria, Pyrus,* Rhamnaceae, *Robinia, Robinia, Salix, Sambucus nigra, Sorbus, Staphylea, Tilia,* Ulmaceae, *Viscum, Vitaceae*
LCC3	Mixed forest (dominated by a mix of needle-leaf and broad-leaf forest)	Defined by thresholds between different forest types
Semi-open LCC		
LCC4	Semi-open vegetation (mixed land cover including both forest and open vegetation)	Defined by thresholds between other classes
Open LCCs		
LCC5	Heath/scrubland	*Aellenia, Alkanna, Anagallis, Arctostaphylos, Argania spinosa, Asphodelus, Astragalus, Ballota, Beta, Bongardia, Calluna, Carex, Casuarina, Centaurea sclerophyllus, Ceratonia, Chaenorhinum, Chamaerops, Chrozophora, Cistaceae, Citrus, Colchicum, Colutea, Convolvulaceae, Coriaria, Cynoglossum, Cyperaceae, Cytisus, Echium, Empetrum, Ephedra, Erica, Fagonia, Genista, Hippophae, Hypericum pulchrum, Hyphaene, Juniperus, Laurus, Lotus, Melampyrum pratense, Moltkia, Narthecium, Onosma, Parnassia, Phlomis, Pistacia, Polygonum* heath types, evergreen *Quercus, Rhynchospora, Rosmarinus, Rutaceae, Salvia, Sapotaceae, Sarcobatus, Scheuchzeria, Tamarix, Trachycarpus, Ulex,* Valerianaceae heath types, *Verbena*
LCC6	Pasture/natural grassland	*Actaea, Agrimonia, Anemone, Anethum, Anthyllis,* Apiaceae, *Asperula, Asteraceae (*subfamily *Lactucoides), Asteraceae* undifferentiated, *Bunium, Bupleurum, Calendula, Caltha,* Campanulaceae, *Centaurea* grassland types, *Coronilla,* Dipsacaceae, *Epilobium, Filipendula, Galega, Galium, Gentianaceae, Geum, Knautia, Lithospermum officinale, Ornithopus, Paliurus spina christi,* Papaveraceae, *Plantago alpina, Plantago coronopus, Plantago lanceolata, Plantago tenuiflora,* Poaceae, *Polygala, Potentilla,* Ranunculaceae, *Rhinanthus, Rumex acetosa, Rumex acetosella, Ruppia, Sanguisorba, Senecio, Sherardia arvensis, Sisyrinchium,*

		Stachys, *Succisa*, *Thalictrum*, *Trifolium*, Urticaceae, Valerianaceae grassland types, *Veronica*, Viciaceae
LCC7	Arable/disturbed land	*Allium, Anagallis arvensis*, *Anchusa*, *Aphanes*, *Arctium*, *Artemisia*, Asparagaceae, Asteraceae (subfamily Asteroideae)*, Borago, Brassicaceae, Calligonum*, Cannabaceae*, Carduus*, Caryophyllaceae, *Cassia*, *Centaurea* arable types, *Centaurea* undifferentiated, *Cerealia*, Chenopodiaceae, *Cirsium, Cucurbitaceae, Fagopyrum, Galeopsis, Humulus, Hypericum calycinum, Jurinea, Lamiaceae, Lappula, Lathyrus*, Leguminosae, Linaceae, *Lithospermum arvense, Medicago, Melilotus, Noaea, Ononis, Pastinaca sativa, Phaseolus, Pisum*, Plantaginaceae, *Plantago albicans*, *Plantago atrata, Plantago cylindrica*, *Plantago major*, *Plantago maritima*, *Plantago media, Plantago montana*, *Plantago ovata*, *Plantago psyllium*, *Polygonaceae arable types, Prosopis*, *Punica, Rheum, Ribes*, *Ricinus*, *Rubus* arable types*, Rumex type, Scorzonera, Sideritis,* Silenaceae, Solanaceae, *Spinacia*, Valerianaceae arable types, *Zea*
LCC8	Mixed open vegetation (dominated by a combination of heath/scrubland, pastures/natural grassland and arable land)	Defined by thresholds between open classes

Table 2 Land cover classes (LCCs) defined for the pseudobiomization (PBM) method

	Land Cover Class	**Description**
Closed LCCs		
LCC1	Needle-leaf forest	Defined by a small number of needle-leaf trees (typically high pollen producers)
LCC2	Broad-leaf forest	Defined by a large number of broad-leaf trees (e.g. deciduous *Quercus*), including a small number of epiphytes (e.g. *Hedera*), and some fruit trees (e.g. *Olea*)
LCC3	Mixed forest	Dominated by a mix of needle-leaf and broad-leaf forest Defined by thresholds between different forest types
Semi-open LCC		
LCC4	Semi-open vegetation	Mixed land cover including both forest and open vegetation Defined by thresholds between other classes
Open LCCs		
LCC5	Heath/scrubland	Defined by a mixture of heath/scrub type taxa, including evergreen *Quercus.*
LCC6	Pasture/natural grassland	Predominantly defined by a large mixture of grassland herbs including a number of taxa associated with pasture
LCC7	Arable/disturbed land	Defined by a large number of herbaceous taxa indicative of arable and disturbed land (excluding fruit trees)
LCC8	Mixed open vegetation	Dominated by a combination of heath/scrubland, pastures/natural grassland and arable land Defined by thresholds between open classes



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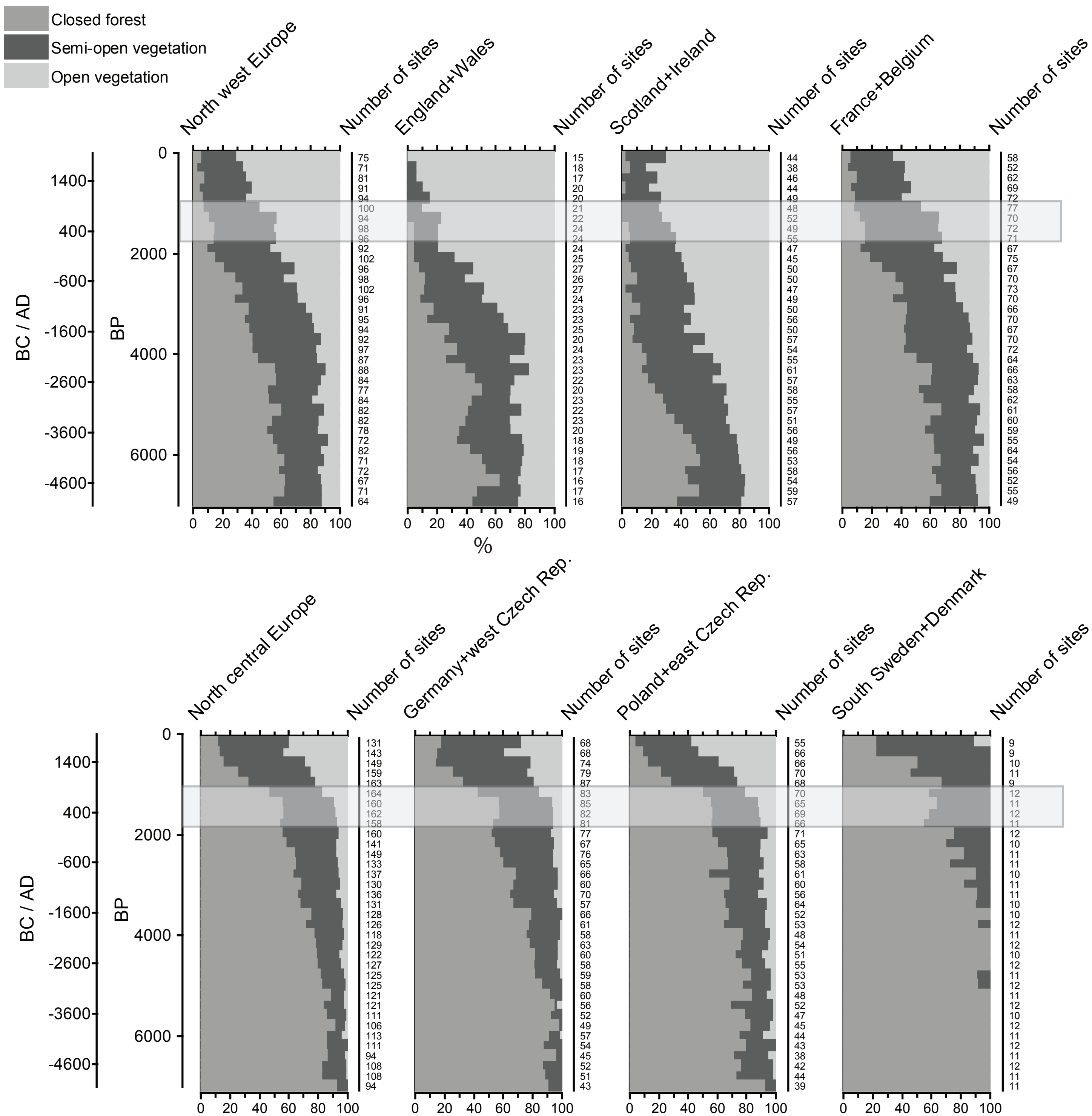
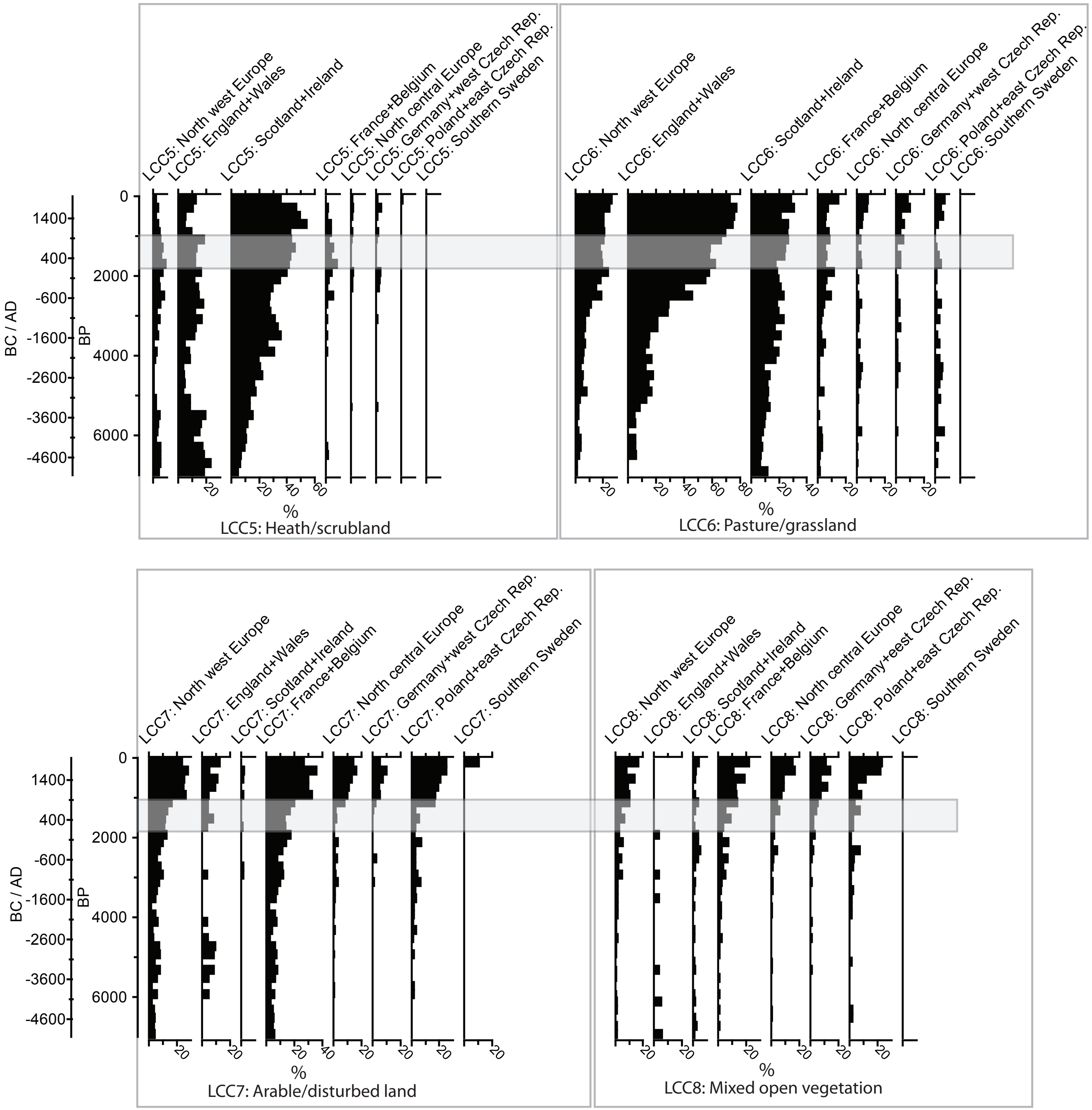
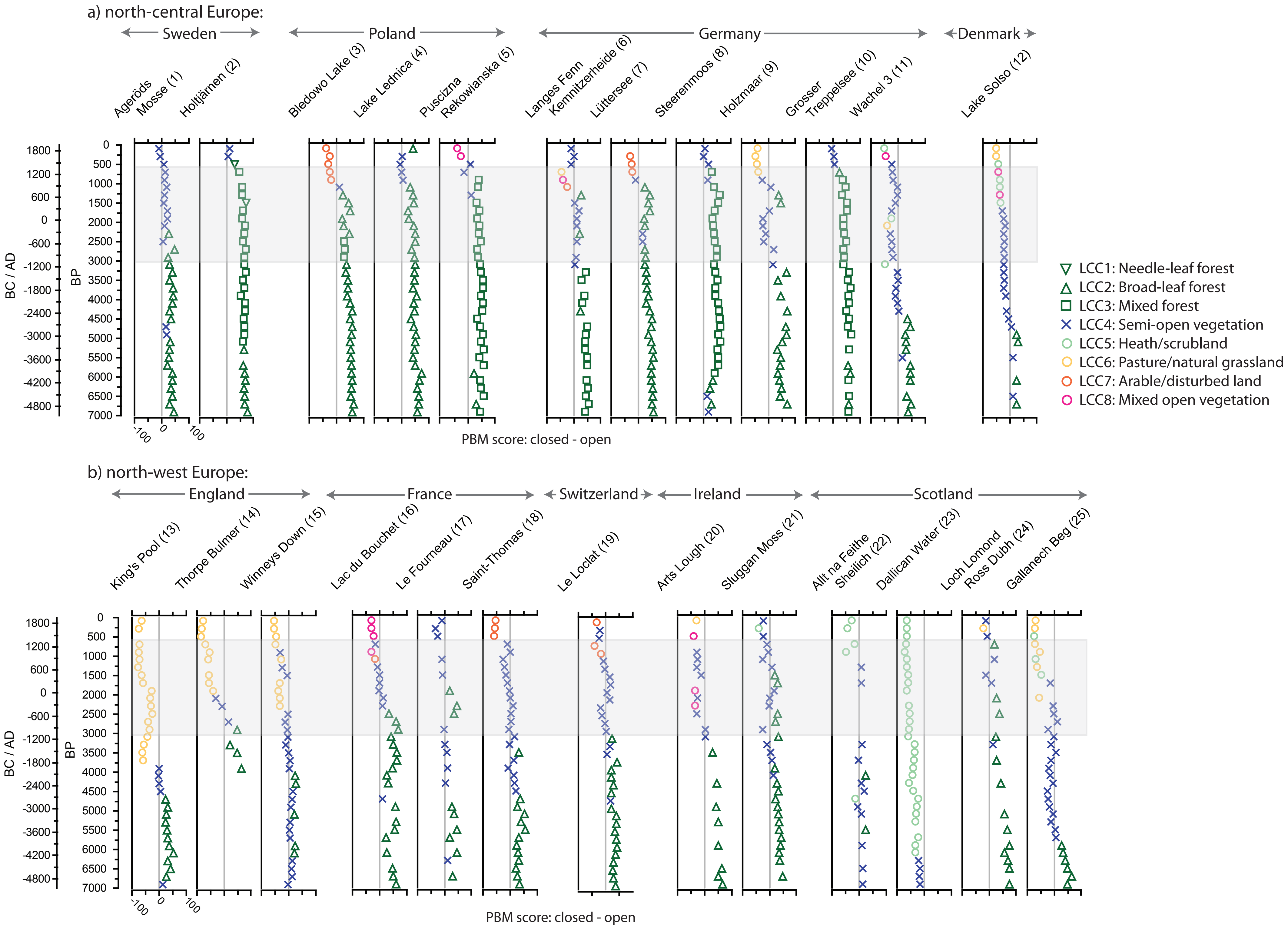
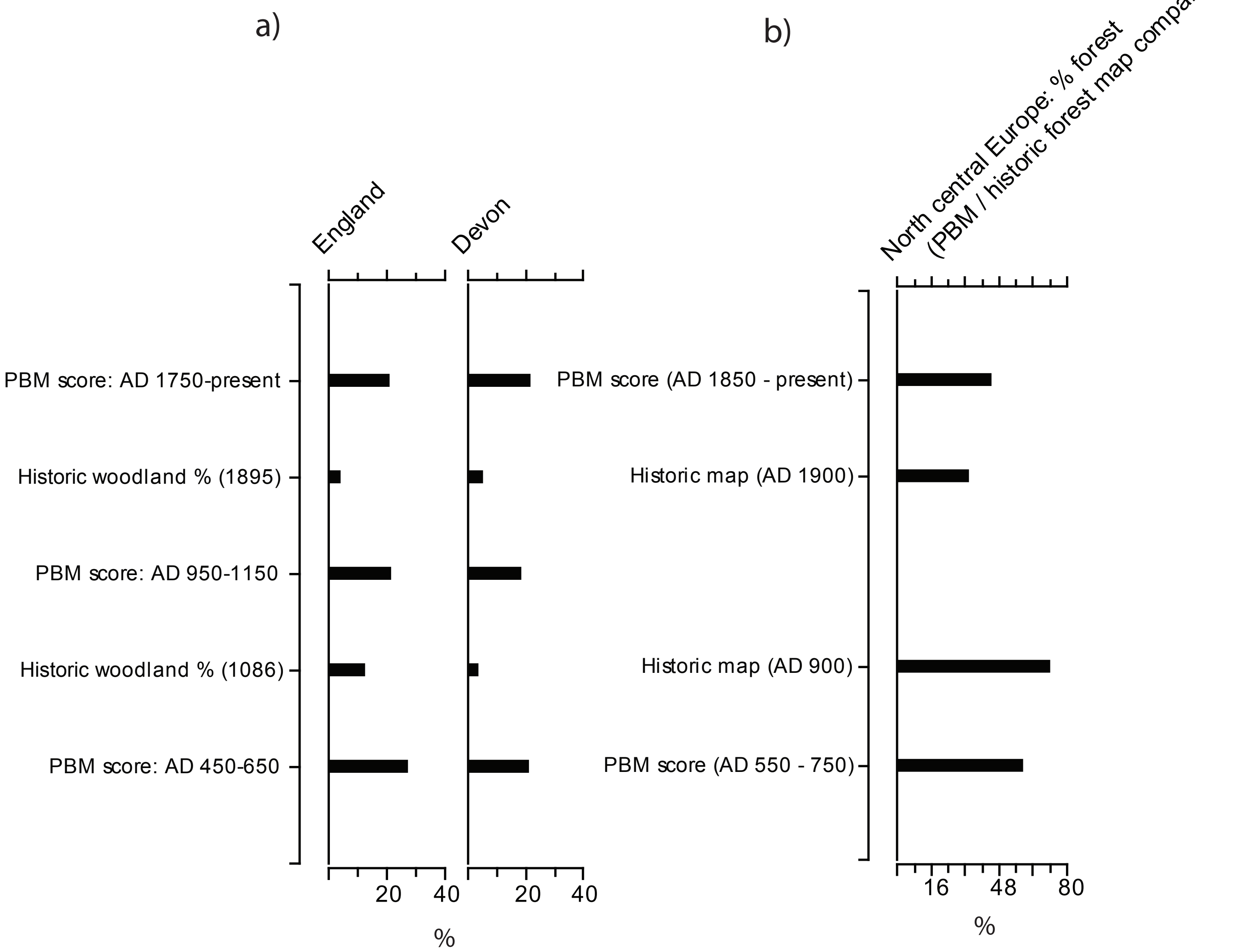
Rome
North west Europe
England + Wales
France + Belgium
Scotland + Ireland
North central Europe
Germany + west Czech Rep.
Poland + east Czech Rep.
Southern Sweden + Denmark
Maximum extent of the Roman Empire in Late Antiquity



Closed forest
Semi-open vegetation
Open vegetation
North west Europe
England+Wales
Scotland+Ireland
France+Belgium
North central Europe
Germany+west Czech Rep.
Poland+east Czech Rep.
South Sweden+Denmark
Number of sites
BC / AD
BP
%
0 20 40 60 80 100
0
2000
4000
6000
1400
400
-600
-1600
-2600
-3600
-4600


LCC5: North west Europe
LCC5: England+Wales
LCC5: Scotland+Ireland
LCC5: France+Belgium
LCC5: North central Europe
LCC5: Germany+west Czech Rep.
LCC5: Poland+east Czech Rep.
LCC5: Southern Sweden
LCC5: Heath/scrubland
LCC6: North west Europe
LCC6: England+Wales
LCC6: Scotland+Ireland
LCC6: France+Belgium
LCC6: North central Europe
LCC6: Germany+west Czech Rep.
LCC6: Poland+east Czech Rep.
LCC6: Southern Sweden
LCC6: Pasture/grassland
LCC7: North west Europe
LCC7: England+Wales
LCC7: Scotland+Ireland
LCC7: France+Belgium
LCC7: North central Europe
LCC7: Germany+west Czech Rep.
LCC7: Poland+east Czech Rep.
LCC7: Southern Sweden
LCC7: Arable/disturbed land
LCC8: North west Europe
LCC8: England+Wales
LCC8: Scotland+Ireland
LCC8: France+Belgium
LCC8: North central Europe
LCC8: Germany+eest Czech Rep.
LCC8: Poland+east Czech Rep.
LCC8: Southern Sweden
LCC8: Mixed open vegetation
BC / AD
BP
%
1400
400
-600
-1600
-2600
-3600
-4600
0
2000
4000
6000
20
40
60
80


a) north-central Europe:
Sweden
Poland
Germany
Denmark
Agerödş Mosse (1)
Holtjärnen (2)
Bledowo Lake (3)
Lake Lednica (4)
Puscizna Rekowianska (5)
Langes Fenn Kemnitzerheide (6)
Lüttersee (7)
Steerenmoos (8)
Holzmaar (9)
Grosser Treppelsee (10)
Wachel 3 (11)
Lake Solso (12)
BC / AD
BP
PBM score: closed - open
LCC1: Needle-leaf forest
LCC2: Broad-leaf forest
LCC3: Mixed forest
LCC4: Semi-open vegetation
LCC5: Heath/scrubland
LCC6: Pasture/natural grassland
LCC7: Arable/disturbed land
LCC8: Mixed open vegetation
b) north-west Europe:
England
France
Switzerland
Ireland
Scotland
King's Pool (13)
Thorpe Bulmer (14)
Winneys Down (15)
Lac du Bouchet (16)
Le Fourneau (17)
Saint-Thomas (18)
Le Loclat (19)
Arts Lough (20)
Sluggan Moss (21)
Allt na Feithe Sheilich (22)
Dallican Water (23)
Loch Lomond Ross Dubh (24)
Gallanech Beg (25)
BC / AD
BP
PBM score: closed - open



a)
England
Devon
PBM score: AD 1750-present
Historic woodland % (1895)
PBM score: AD 950-1150
Historic woodland % (1086)
PBM score: AD 450-650
20
40
20
40
%
b)
North central Europe: % forest
(PBM / historic forest map comparison)
PBM score (AD 1850 - present)
Historic map (AD 1900)
Historic map (AD 900)
PBM score (AD 550 - 750)
16
48
80
%